National Aeronautics and Space Administration

NASA TECHNOLOGY TRANSFER PROGRAM

BRINGING NASA TECHNOLOGY DOWN TO EARTH

MODULAR DAMAGE DETECTION FOR EXPANDABLE STRUCTURES

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Agenda

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- Background
- Sensor System Design & Attributes
- Sensory Panel
- Embedded Software
- Graphical User Interface
- Testing and Demonstration
- Summary
- Questions & Answers

Background

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Micrometeoroids (MM) & Orbital Debris (OD) are serious threats to International Space Station (ISS) & extraterrestrial habitats

- NASA classes MM & OD as primary threats to commercial crew vehicles
  - See article https://www.nasaspaceflight.com/2016/08/nasa-mmod-primary-threat-crew-vehicles/
- July 2014, radiator damage observed after review of downlinked camera inspection imagery
  - See article http://www.nasaspaceflight.com/2014/07/iss-managers-evaluating-mmod-radiator/

Structural health monitoring and damage detection technologies are identified as critical needs in multiple NASA technology roadmaps

Background

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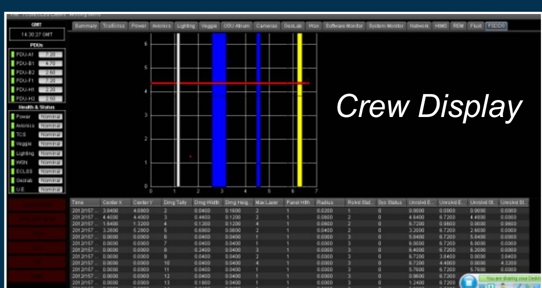
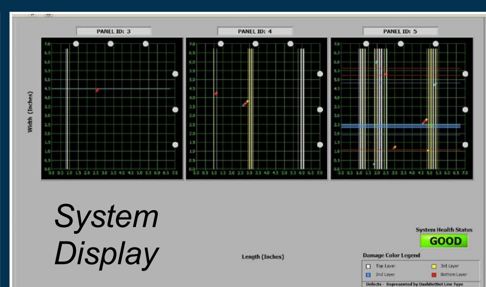
NASA Kennedy Space Center (KSC) has extensive experience developing damage detection technologies

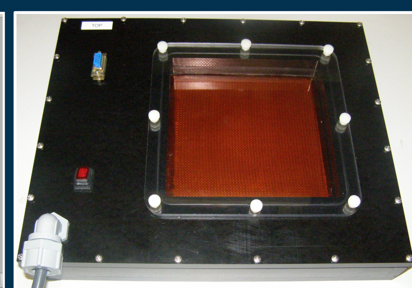
- U.S. Patents 9,233,765; 9,635,302,B2; 10,138,005
- Demonstrated single panel system for Habitat Demonstration Unit (HDU) field demonstration at D-RATS
- Demonstrated damage detection system with multiple sensory panels in crew display avionics for HDU & remote testing capability using secure network (between KSC & JSC)

Desert Research and Technology Studies (D-RATS) 2011

HDU Integrated Demonstration 2012







Sensor System Design

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Modular Damage Detection System (MDDS) is an intelligent damage detection “skin”

- Attached to structures or embedded into composites
- Technology based on sensing electrical integrity of conductive traces
    - When an impact occurs, traces are broken
- Several sensing layers can be implemented in desired pattern
- Design is tailorable for interior and/or exterior applications
    - Sensing panel material, size, and trace spacing can be customized per application
- Provides lightweight in-situ health monitoring capability

MDDS consists of three main subsystems

- Sensory Panel(s)
- Interface board w/ embedded software for situational awareness and damage detection
- Mobile device with graphical user interface (GUI) to operate/monitor system

Sensor System Attributes

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MDDS architecture is flexible and expandable, supporting one or many Sensory Panels organized two-dimensionally in linear or grid patterns

Sensory Panel(s) attributes:

- Active or passive depending on application
- Low power consumption (battery or power supply)
- Interchangeable & Modular: Identical hardware & software
- Operate independently or as multi-panel system
- GUI on mobile device allows users to configure, command, and monitor Sensory Panels wirelessly

Sensory Panel Evolution

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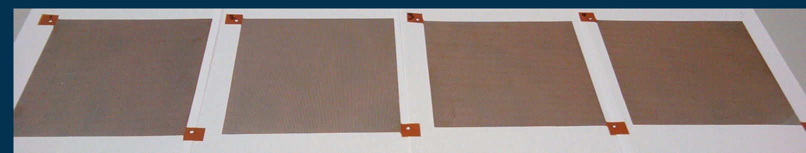
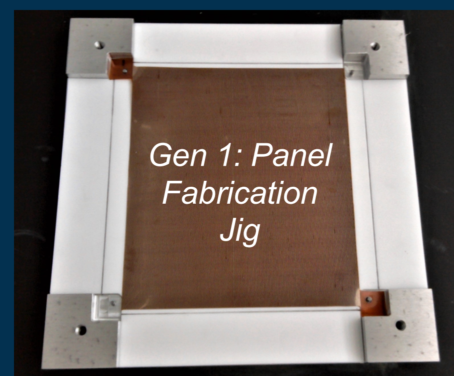
Gen 1: Flexible Sensory Panels printed in-house using conductive ink & assembled

Gen 2: Flexible Sensory Panels fabricated by Printed Circuit Board manufacturer & assembled

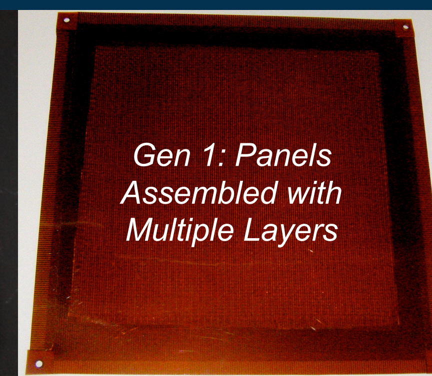
Gen 1: Four panels printed



Ag Ink 20 mil



Gen 1: Panel Fabrication Jig



Gen 1: Panels Assembled with Multiple Layers

Gen 2: Panels Assembled with Multiple Layers

Sensory Panel Evolution

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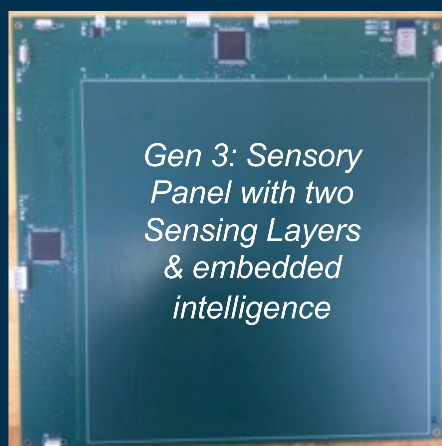
Gen 3: Rigid Sensory Panels with two sensing layers, microcontrollers, embedded software, and Bluetooth wireless communication

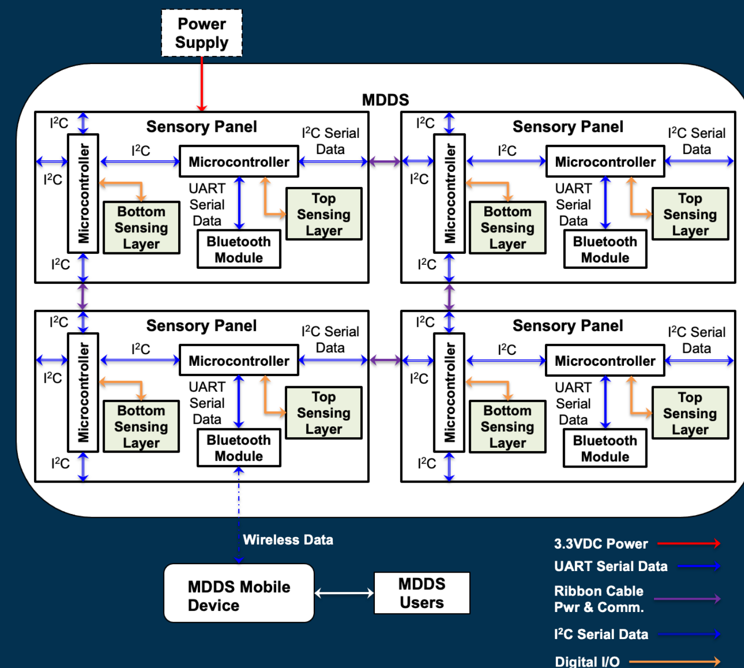
- Sensing Layers oriented orthogonally creating 2D grid
- Embedded software for situational awareness & damage detection
- Low power consumption – less than 500mW / panel

Each Sensing Layer has 96 parallel conductive traces with trace-to-trace spacing of approximately 50 mils



Gen 3: Sensory Panel with two Sensing Layers & embedded intelligence

Dimensions: 9.5 x 9.5 x 0.062 in. (W x L x D)



Notional MDDS Architecture Block Diagram with Four Sensory Panels

Sensory Panel Evolution

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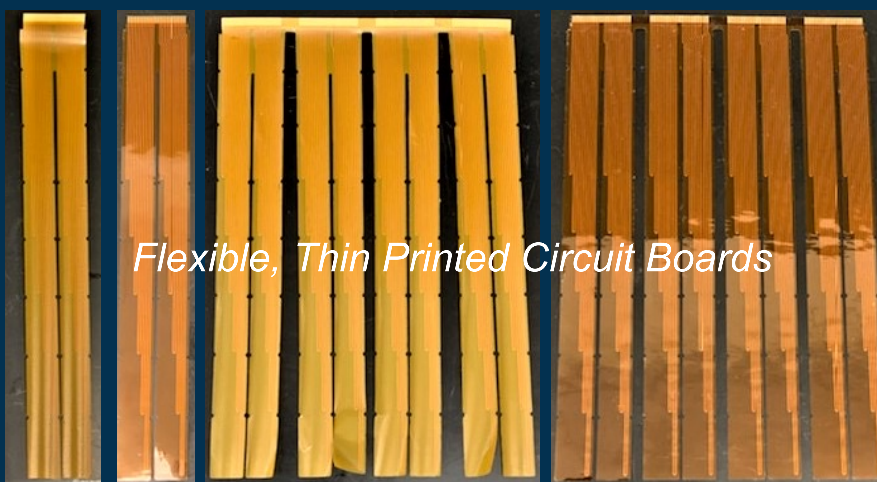
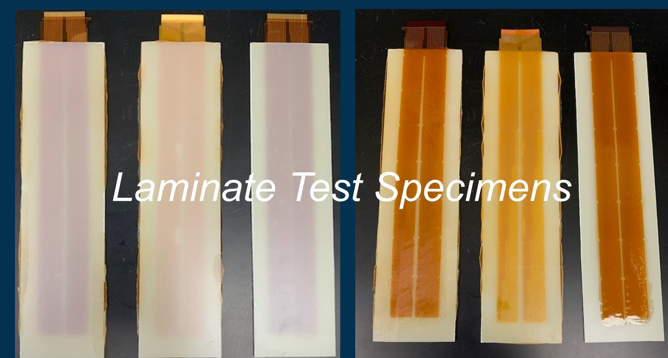
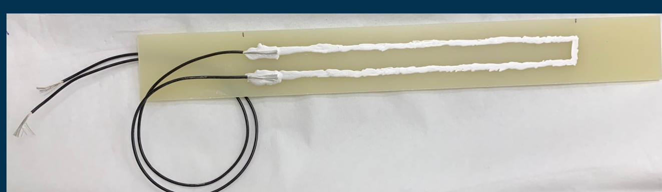
Gen 4: Flexible Sensory Panels for composite applications



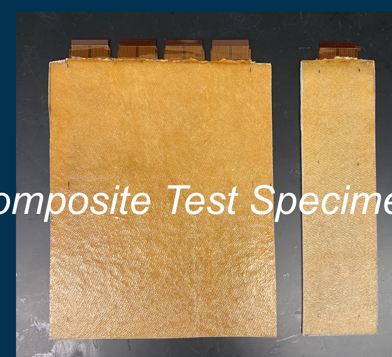
Flexible, Thin Printed Circuit Boards



Laminate Test Specimens



Painted-On Sensory System



Composite Test Specimens

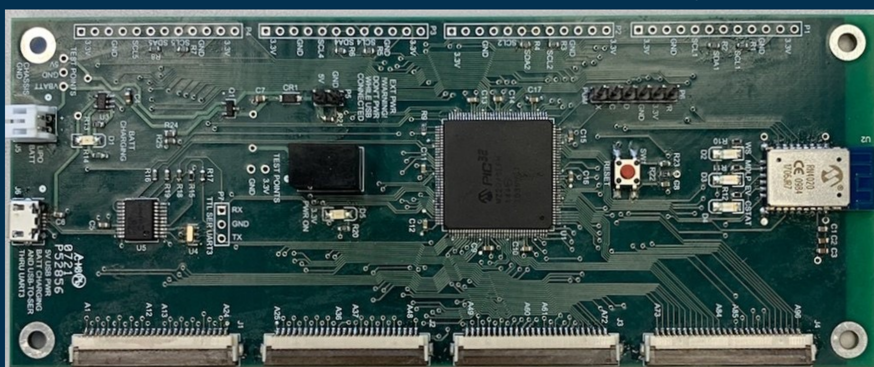
Interface Evolution

Interfacing with flexible Sensory Panels evolved

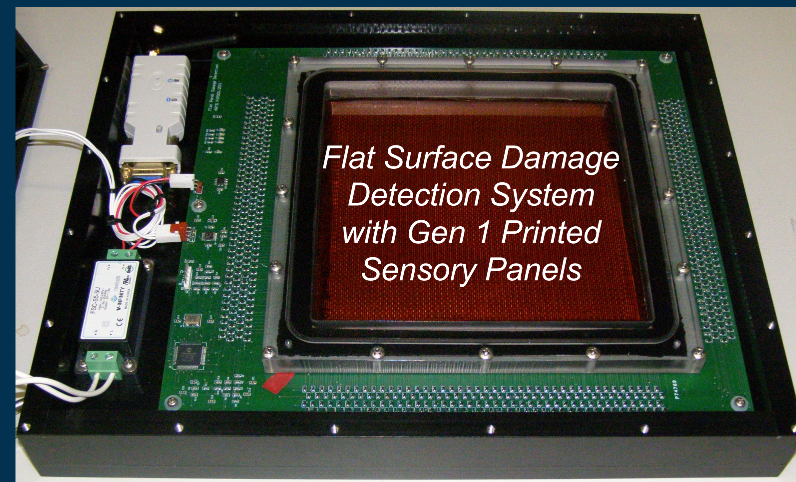
- Gen 1 & 2: Multi-layer panel conductive traces connected to interface frame by solderless method (compression)
- Gen 4: Interface board designed to monitor up to 4 Finger-based Sensory Panels

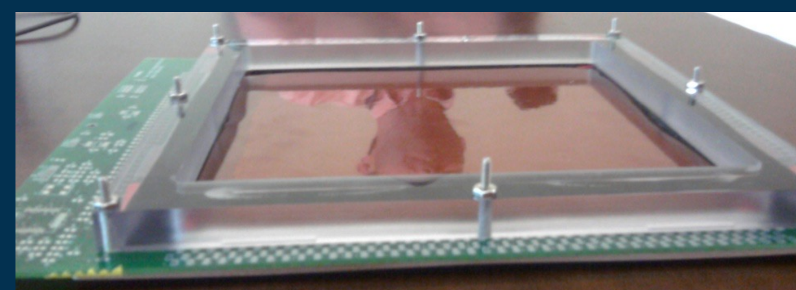
Gen 4 Electrical Interface Board for 4 Sensory Panels

Dim: 2 x 4 in. (W x L)



4 Zero-Insertion Force (ZIF) connectors





Gen 2 Sensory Panels with Compression Ring

Software Evolution

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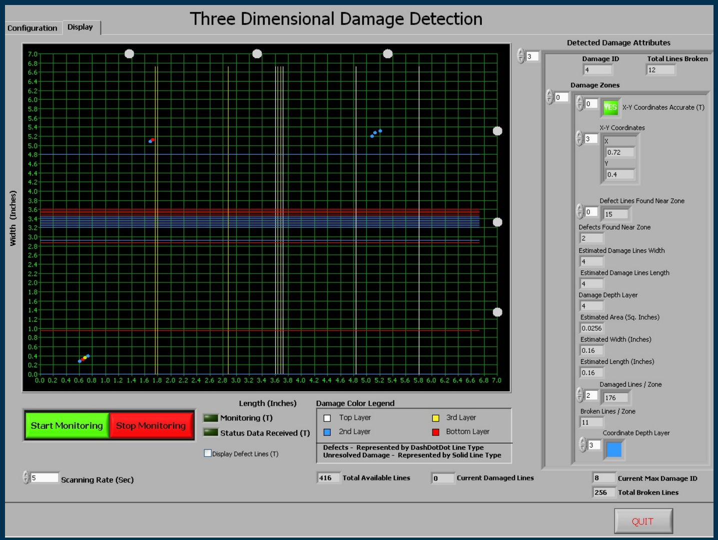
Gen 1 & 2: Embedded software ONLY monitored & reported electrical integrity of conductive traces

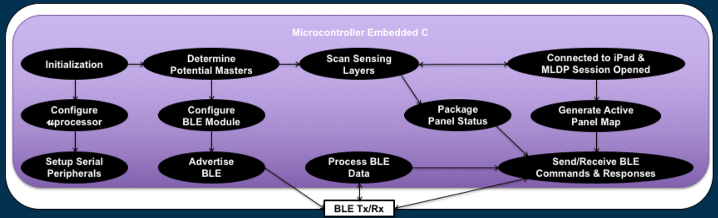
- Custom LabView software provided GUI to control/monitor panels & process results to identify, locate & visualize impact damage

MDDS: Embedded software evolved to handle wireless communication, multi-panel situational awareness & damage detection algorithms to locate damage

- Processes/responds to commands from mobile device & reports Sensory Panel health status upon request
- Executes algorithms to:
  - Determine Master Panels (MPs) & assign MP via GUI
  - Generate active panel map
  - Monitor health status of all active panels



Gen 1 & 2: LabVIEW GUI



Embedded Software Logical Overview

Embedded Software

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Sensory Panel initialization & active panel map operations:

- Each panel checks presence of an active panel to its left and/or below it using I2C serial interfaces to determine potential Master Panels (MPs)
    - If no active panels are present to left or below, assigns panel as potential MP & configures Bluetooth
    - One or more potential MPs could be present since configuration is arbitrary
- Once user assigns MP using GUI, all other panels become normal active panels
- Newly-assigned MP starts progressive scan using active panel mapping algorithm to determine spatial relationship to other active panels
    - Communicates with adjacent panels to determine its closest neighboring panels
    - Requests adjacent neighbors to report status of their respective neighbors until no new panels are found
    - Maintains record of the configuration & path to access any active panel

Embedded Software

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Each Sensory Panel continuously monitors its health

- Damage detection algorithm evaluates health status injecting test pulses periodically on sensing traces to determine electrical integrity
    - If traces are broken, algorithm calculates location of any faults
    - Relative time stamp is associated with each damage event to establish order of events
        - Helps organize & identify location of damage if subsequent damages occur on same panel later

GUI periodically requests health status from MP of all active panels

- MP gathers, coordinates, and packages damage information and sends it wirelessly to GUI
    - Damage location is reported in rectangular boundaries (bottom left-hand to upper right-hand corners)
    - When damage is detected on top Sensing Layer ONLY, exact damage location is undermined
        - Reports corresponding location in x-axis only

MDDS GUI

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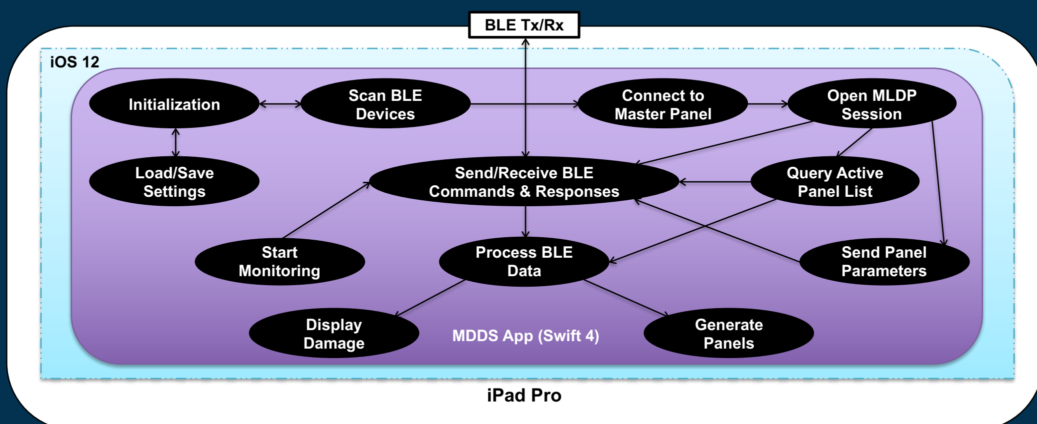
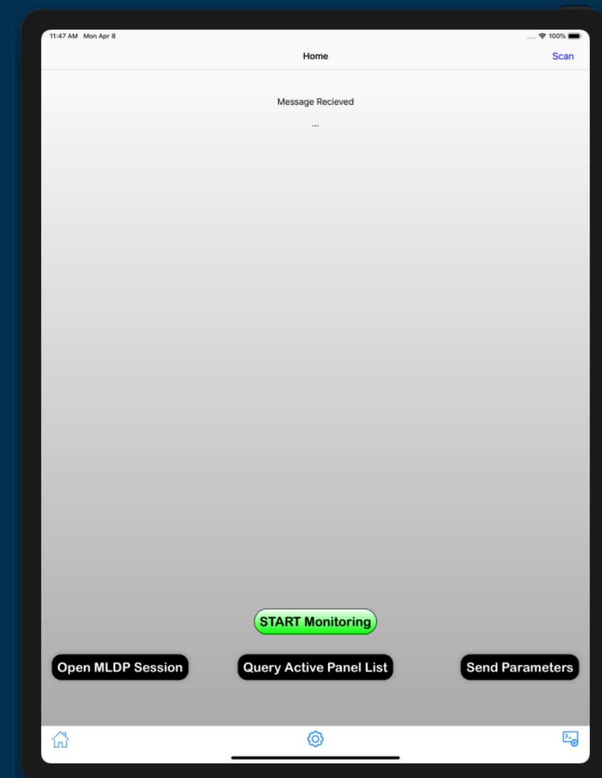
MDDS App designed for 3rd gen iPad Pro

- Written in Swift
- GUI allows users to configure, command, control, monitor, and display health status of active Sensory Panels in system
- Receives telemetry wirelessly from MP using Bluetooth



MDDS App Software Logical and Structural Overview



MDDS Application Home Page

MDDS: Testing & Demonstration

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Simulated test data used to evaluate MDDS App performance

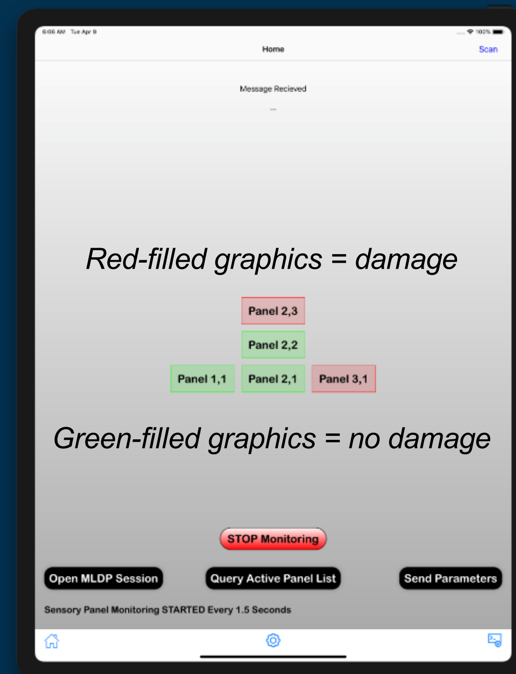
- Data set consisted of five Sensory Panels laid out in inverted-T pattern

System Operations:

- During initialization, Sensory Panels determine whether they're a potential MP
- User scans for BLE advertisements, assigns MP, configures Sensory Panel settings, and opens BLE private communication service to send & receive information wirelessly
- User requests query of active panels from MP & begins monitoring system
- Sensory Panel health information displayed by clicking on panel graphic

Sensory Panels Layout for Testing

GUI Displaying Sensory Panel Health Status



MDDS: Testing & Demonstration

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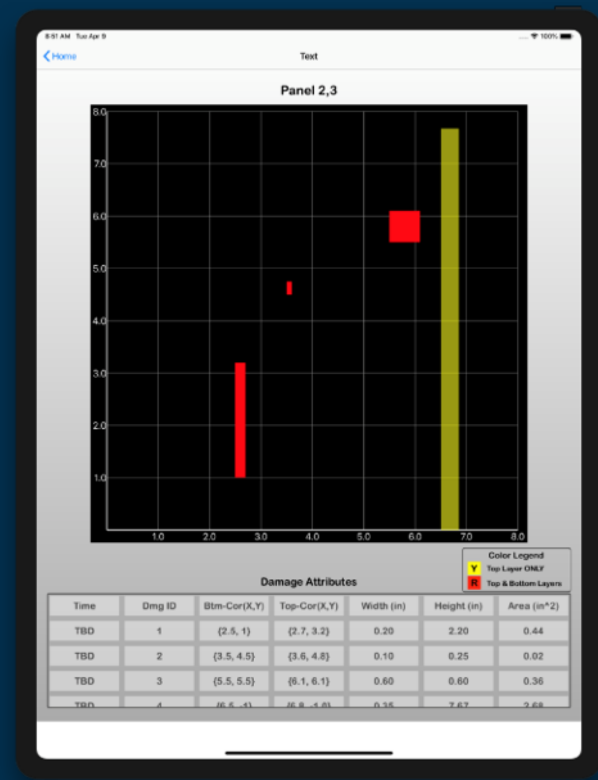
Panel 2,3 GUI shows four simulated damage areas:

- Three rectangular/square in red
  - Damage resulting in broken conductive traces on top & bottom Sensing Layers
- One top-only damage in yellow
  - X-only coordinate provided; no y-coordinate can be assigned

Damage details displayed in tabular format

- Damage ID number is assigned
- Bottom left-hand corner & top right-hand corner x- and y-coordinates are shown
- Damage width, height, and calculated area are displayed



Detailed Damage Information for Panel 2,3

Composites: Testing & Demonstration

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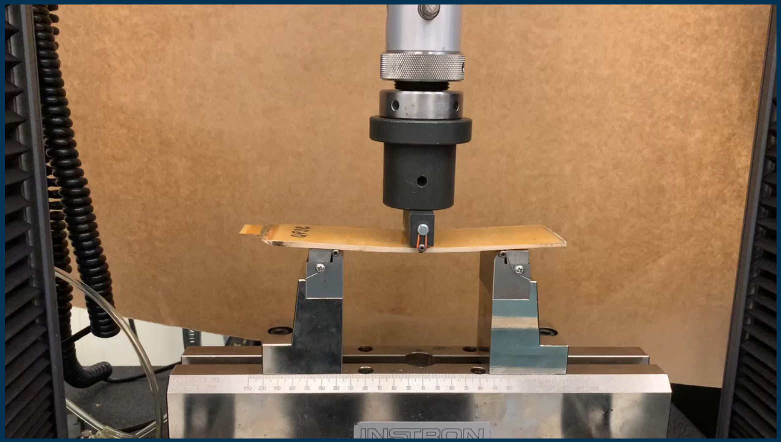
Panels were exposed to two types of tests to simulate/induce damage: 3-point bend & fatigue

- 3-point bend testing performed per modified version of ASTM D7264
  - Modifications due to differences between specimens provided and those required by standard
  - Goal was to determine if failure of fiberglass face sheets cause ripping/tearing of adhered flexible circuitry
- Low-cycle threshold fatigue test using 3-point flexural test setup
  - Testing conducted where test specimen was subjected to low load & high load for 100 cycles
  - After 100 cycles, test specimen was connected to interface board for damage assessment
  - If no damage observed, low & high loads increased for 100 additional cycles
  - Process continued until damage was detected or sample failed under load

Low-cycle threshold fatigue testing



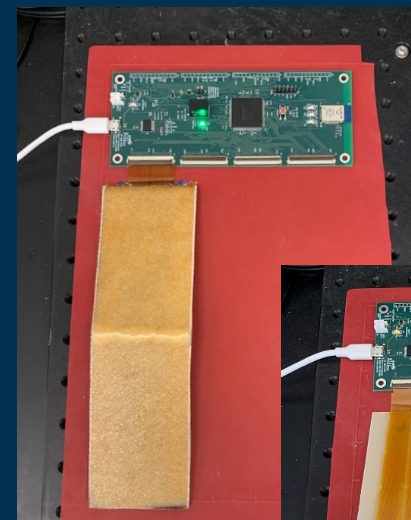
Composites: Testing & Demonstration

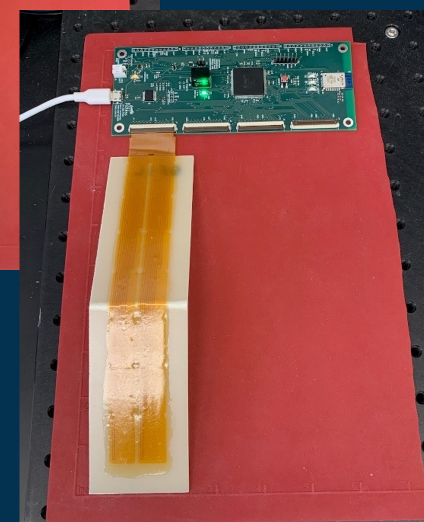
Testing Results – 3-point Bend

- Composites (Fully Encapsulated)
  - 2-finger thin, flexible PCBs showed detectable damage after 3-point bend testing to failure
  - Thin, flexible PCB from Vendor A did not show detectable damage after initial 3-point bend test & only showed damage after flexing
  - Ability to detect damage in composite materials can be greatly impacted by thickness of composite material (face-sheet thickness)
- Laminates (Partially Encapsulated)
  - 2-finger thin, flexible PCBs showed detectable damage after 3-point bend testing to failure

Testing Results – Fatigue

- Results from fatigue testing were not conclusive due to specimen failure





Interface board damage detection data collection

Summary

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NASA KSC has been developing and successfully demonstrating damage detection technologies for years

MDDS provides an attractive option for applications where in-situ health monitoring is needed

- Design is tailorable for interior and/or exterior applications
- Architecture is flexible and expandable, supporting one or many Sensory Panels
    - Algorithms provide for situational awareness, self-configuration, and damage detection & localization
    - Supports wireless communication using Bluetooth technology
- Sensory Panels are modular and interchangeable
    - Same hardware and software; low power consumption – less than 500mW / panel
- MDDS App provides users a simple & attractive method to interact with system
- Embedding thin, flexible circuitry into composites does not appear to impact composites overall structural integrity

Acknowledgements

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Questions

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